CALiPER

Roundtable Report

March 2009

DOE Solid-State Lighting CALiPER Program

2009 Roundtable

Prepared for the U.S. Department of Energy by
Pacific Northwest National Laboratory

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Building Technologies Program
Solid-State Lighting Research and Development Portfolio
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ACKNOWLEDGEMENTS

The Department of Energy would like to acknowledge and thank all of the Roundtable participants (listed in the Appendix) and their companies for their active engagement in this effort. The Department would also like to thank all the direct contributors and especially the following individuals:

Bob Berger, Independent Testing Laboratory
Andrew Jackson, Philips Lighting Company
Dave Jenkins, Orb Optronix
Ian Lewin, Lighting Sciences Laboratory
Jeff McCullough, Pacific Northwest National Laboratory
Cameron Miller, National Institute of Standards and Technology
Eric Milz, Philips Lumileds
Yoshi Ohno, National Institute of Standards and Technology
Mia Paget, Pacific Northwest National Laboratory
Eric Richman, Pacific Northwest National Laboratory
Terry Shoemaker, Pacific Northwest National Laboratory
Heidi Steward, Pacific Northwest National Laboratory
Alan Tirpak, Optronic Laboratories
Yuqin Zong, National Institute of Standards and Technology

Thanks to all for such an enriching, constructive event.

Prepared for the U.S. Department of Energy by Pacific Northwest National Laboratory under Contract DE-AC05-76RLO 1830.

COMMENTS

The Department of Energy is interested in feedback or comments on the materials presented in this workshop report. Please write directly to:

James R. Brodrick, Ph.D.
Lighting R&D Manager
EE-2J/Forrestal Building
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585-0121

DOE Solid-State Lighting
CALiPER Program

CALiPER Roundtable 2009 Proceedings

ML Paget
EE Richman
HE Steward
JJ McCullough

March, 2009

Prepared for
The U.S. Department of Energy
Under Contract DE-AC05-76RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

Building Technologies Program
Energy Efficiency and Renewable Energy
U.S. Department of Energy

DOE Solid-State Lighting CALiPER Roundtable 2009

Introduction

On March 3 & 4, 2009, the Department of Energy's Building Technologies Program hosted a roundtable meeting among standards-setting efforts, lighting testing laboratories, and key stakeholders in the solid-state lighting (SSL) industry. This roundtable discussion built upon DOE-led sessions on SSL testing standards held in 2006 and 2007.[1] For the 2009 roundtable meeting, over 30 experts from key national efforts – such as Illuminating Engineering Society of North America (IES), International Association of Lighting Designers (IALD), National Institute of Standards and Technology (NIST), National Electrical Manufacturers Association (NEMA), American National Standards Institute (ANSI) – and independent photometric testing laboratories, SSL manufacturers, and research laboratories gathered in Denver, Colorado to discuss current issues related to SSL testing and related standards development.

James Brodrick, U.S. Department of Energy (DOE) SSL Portfolio Manager, welcomed the participants and emphasized the importance of this meeting in the broader context of the DOE's SSL activities which are helping to bring high-quality, energy-efficient SSL technologies to market. By working together, the CALiPER Roundtable participants help to identify issues, consider options, and establish paths forward for DOE SSL commercial product testing and other DOE SSL commercialization support activities, the standards communities, and SSL manufacturers. The 2009 CALiPER Roundtable is the fourth gathering hosted by DOE to provide leadership and support to accelerate the LED standards development process.

The roundtable meetings are tight-knit, constructive sessions requiring active participation of all attendees. The first day of the roundtable aimed at broadly identifying current advances and issues surrounding SSL testing, via short presentations and group discussions surrounding key topic areas: progress of standards efforts and CALiPER testing, LED subcomponent testing, SSL luminaire photometry, ENERGY STAR® for SSL testing, and life-testing. The second day was dedicated to intensive breakout sessions in each key

[1] An initial DOE-hosted SSL Standards Workshop was held in March, 2006. A second DOE-hosted workshop was held in October, 2006 along with a kick-off workshop for the DOE's commercial product testing program (later named CALiPER). A third DOE-hosted standards workshop and CALiPER Roundtable meeting was held in November, 2007. Proceedings from the November 2007 Roundtable meeting are available online (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2007_caliper_roundtableproceedings.pdf).

subject area to prioritize issues, explore options, and define paths forward for key stakeholder groups to address the various issues. The presentation topics are summarized briefly below, followed by highlights of the working sessions on each topic.

Summary of Presentations from the CALiPER Roundtable

LED Standards and Test Methods Progress Update and What's in the Oven

Eric Richman of Pacific Northwest National Laboratory (PNNL) summarized the current status of the development of LED standards and test methods, citing an impressive list of efforts which have been completed or initiated since the initial DOE standards workshop on March 6, 2006. Numerous performance standards, test methods, safety standards, and other related standards impacting SSL and LED products are currently under development, including (but not limited to):[2]

- Completed standards, test methods, and CIE/IEC counterparts
  - ANSI C78-377 (chromaticity)
  - IES LM-79 (luminaire photometric testing)
  - IES LM-80 (LED module lumen depreciation testing)
  - IES RP-16 Addendum "a" (LED definitions)
  - CIE TC2-45 CIE 127-2007 Measurement of LEDs
  - CIE TC1-62 177-2007 Colour Rendering of White LED Light Sources
  - IEC SC 34A - TS 62504 Terms and Definitions for LEDs and LED Modules in General Lighting

- Additional primary standards identified or underway
  - CIE TC1-69 Color Quality Scale (new CRI type metric)
  - C82.SSL1 LED Drivers
  - UL 8750 Safety
  - TM-21 Lumen Maintenance Extrapolation Method
  - LM-XX1 Methods for the Measurements of High Power LEDs
  - LM-XX2 LED "Light Engine" Measurements (PIF for approval)
  - LM-XX2 Photometric Testing of Outdoor LED Luminaires (based on LM-10/31)
  - RP-16 Additional LED Definitions
  - C78.SSL2 LED Sub-assembly Interfaces
  - C78.SSL3 Binning Standards
  - C78.SSL4 Form Factors
  - ANSI SSL2 LSD-45 Sockets & Interconnects Consistency Standard
  - ANSI C82.4 Driver Performance Standard
  - CIE TC2-46 CIE/ISO LED Intensity Measurements
  - CIE TC2-50 Optical Properties of LED Arrays
  - CIE TC2-58 Luminance and Radiance of LEDs
  - IEEE P1789 – Recommended Practices of Modulating Current in High Brightness LEDs for Mitigating Health Risks to Viewers
  - IEC SC 34A – Performance Standard for LED Lamps
  - IEC SC 34A 62031:2008 LED Modules - Safety

[2] For more information about solid-state lighting standards, visit http://www.ssl.energy.gov/standards.html , and download the DOE's fact sheet, "LED Measurement Series: Solid State Lighting Standards," http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_standards.pdf.

– IEC SC 34C 61347-2-13:2006 – Lamp Controlgear – Part 2-13: DC or AC Controlgear for LED Modules
– IEC SC 34A IEC 62560 Self-Ballasted LED Lamps
– IEC SC 34A <tbd> LED Lamps > 50 V – Safety Specs

Where CALiPER is Today

In a little over 2 years, the DOE CALiPER program has tested over 200 SSL products and many benchmark lamps and luminaires. Mia Paget of PNNL provided a quick synopsis of current CALiPER activities and recent CALiPER results.

Since the IESNA LM-79 testing method was finalized, a number of independent testing labs have joined the list of laboratories which are qualified for CALiPER testing and have successfully completed CALiPER round-robin testing on SSL products. Various sectors of the lighting industry appear to now be aware of the differences between relative and absolute photometry and many SSL manufacturers are requesting and publishing results from LM-79 photometric testing. CALiPER testing is showing steady improvements in average and maximum levels of SSL product performance, but is still showing huge ranges in performance, from the worst products not meeting performance levels of incumbent technologies, to the best products clearly achieving and surpassing levels of some incumbent technologies.[3]

CALiPER continues to perform absolute photometry on SSL and benchmark products, providing detailed reports, general analyses, and benchmark reports to the public. In addition to the basic photometric testing, CALiPER also explores other aspects of SSL product testing, such as long-term studies, in situ testing, dimming, etc. One purpose of the roundtable meeting is to identify and prioritize these testing options and needs to provide feedback toward the development, refinement, and adoption of credible, standardized test procedures and measurements for SSL products.

Update on the Measurement of High-Power LEDs

Recent research efforts and progress made by independent testing laboratories are contributing to a better understanding of feasible options for reproducible photometric testing of LED chips and modules. Yuqin Zong and Yoshi Ohno (both of NIST) presented their recent progress on methods for measuring high power LEDs.[4] Recent NIST studies are contributing to the development of a CIE recommendation on methods for the operation of high-power LEDs in DC and in pulse mode, at specified junction temperatures, to enable reproducible optical measurements (CIE TC2-63 Optical Measurement of High-Power LEDs, Chair: Yuqin Zong). This research is also contributing to the study of high speed testing methods for electrical, thermal, and optical quantities during the production of LEDs and the conversion of the values to DC operational conditions including the related time dependent functions (TC2-64 High Speed Testing Methods for LEDs, Chair: Guenther Heidel (Germany)). Yoshi Ohno also introduced preliminary discussion of IES efforts toward developing standardized testing methods for LED modules (incorporating heat sinks) or LED engines (incorporating heat sinks and drive electronics).

There are a variety of possible methods for testing LED subcomponents which may depend on both the objectives behind the testing and on the characteristics of artifacts being tested. Subcomponents may be pulse tested or tested in steady-state with either passive or active heat sinks. NIST investigations have

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[3] Summary reports, benchmark reports, and detailed photometric test reports from CALiPER testing are available online (www.ssl.energy.gov/caliper.html). The CALiPER Round 7 Summary Report was issued in January, 2009, (http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/caliper_round_7_summary_final.pdf).
[4] See Yuqin Zong and Yoshi Ohno, New Practical Method for Measurement of High-Power LEDs, Proceedings of the CIE Expert Symposium 2008 on Advances in Photometry and Colorimetry, CIE x033:2008, pp 102-106, http://physics.nist.gov/Divisions/Div840/tcled/docs/practicalMethodsMeasurementHighPowerLEDS.pdf.

revealed differences between testing with active versus passive heat sinks. Testing with passive heat sinks shows significant differences after the first milliseconds and seconds of operation. Testing with active, temperature controlled heat sinks can be correlated to pulse DC testing under set conditions. A key objective is to enable characterization of LED packages as a function of current and temperature using reference drivers. Questions remain as to what temperatures to measure and how to set conditions to enable reliable correlation of performance between pulse testing and steady-state testing.

Dave Jenkins (Orb Optronix) shared details on LED characterization systems which are used in LED binning, qualification, characterization, and thermal engineering.[5] Systems and tools in use today enable rapid testing under multiple conditions (ranges of environmental and drive conditions) to establish families of curves for LED packages and modules and visualize and analyze those curves through interactive software.

Update on Photometric Measurement of SSL Luminaires and Integral Replacement Lamps

Since the publication of the IES LM-79 method for photometric testing of SSL luminaires and integral replacement lamps, the number of labs conducting LM-79 testing and the number of LM-79 tests conducted has risen rapidly. Observing and analyzing this growing number of reports, Heidi Steward and Mia Paget (both of PNNL) led discussions about basic photometric testing of SSL products. Heidi Steward illustrated the variety of reporting practices observed in reports stemming from LM-79 testing. The discussion focused on how much can be standardized or improved in reports and what practices may help to avoid manufacturer misuse of results or reader confusion. Mia Paget provided a quick summary of the CALiPER study of variability and repeatability of SSL testing, based on CALiPER test results to date.[6] These results provide clear reassurance that SSL testing does not appear to have any greater level of uncertainty, on average, than testing of other light sources, and it helps to identify specific aspects of LM-79 testing that could be refined to decrease uncertainties in LM-79 testing.

NIST/NVLAP Process & Proficiency Testing Specifics

Cameron Miller (NIST) introduced the recently issued NIST/ National Voluntary Laboratory Accreditation Program (NVLAP) Process and Proficiency Testing Specifics which now includes LM-79:2008 and LM-80:2008 as program specific applications within the category of energy-efficient lighting products test methods. Mechanisms are established for NVLAP SSL proficiency testing, both for laboratories which already have NVLAP accreditation for other methods and for laboratories which are new to NVLAP accreditation, through bi-lateral proficiency testing followed by round-robin proficiency testing. The DOE is providing support to facilitate the NVLAP process for laboratories seeking LM-79 and LM-80 NVLAP accreditation.[7]

ENERGY STAR for SSL Testing

Jeff McCullough (PNNL) provided an overview of program requirements and ENERGY STAR Criteria for SSL Luminaires. Manufacturers seeking ENERGY STAR qualification of SSL products must complete electrical and photometric testing requirements, based on LM-79 testing at qualified laboratories, and fulfill “life” testing requirements based on LM-80 testing and in situ temperature

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[5] See “Electrical-Thermal-Optical LED Characterization System” from Orb Optronix, http://www.orboptronix.com/pdfs/Orb%20ETO%20LED%20Characterization%20System.pdf.
[6] CALiPER exploratory report available upon request from the DOE: *2008 Summary Report on Testing Variability and Repeatability, U.S. Department of Energy Solid-State Lighting CALiPER Program*, PNNL, January 2009.
[7] See *NIST Handbook 150-1, NVLAP Energy Efficient Lighting Products*, http://ts.nist.gov/Standards/Accreditation/upload/NIST_HB_150_1_2008.pdf, and *NIST Handbook 150-1A, NVLAP Energy Efficient Lighting Products - Solid State Lighting*, http://ts.nist.gov/Standards/Accreditation/upload/NIST-HB-150-1A-2009.pdf.

measurement tests.[8] As an increasing number of product applications are covered by the ENERGY STAR for SSL criteria, an increasing number of manufacturers are seeking ENERGY STAR for SSL testing and questions are being raised and resolved among the independent testing laboratories, manufacturers, standards committees, and the ENERGY STAR for SSL team. A number of questions and possible solutions were discussed during the roundtable meeting.

Tool for Verifying Spatial Uniformity of Color

The ENERGY STAR for SSL criteria includes a requirement for spatial uniformity of color: "The variation of chromaticity in different directions (i.e., with a change in viewing angle) shall be within 0.004 from the weighted average point on the CIE 1976 (u',v') diagram." Eric Milz (Philips Lumileds) introduced a tool available online (http://philips.pnwsoft.com/) for aiding in checking compliance with this requirement, the "Solid State Luminaire Chromaticity and Color Spatial Uniformity Compliance Checker for ENERGY STAR." The tool is available at no charge and simple to use with any data set of Intensity or Illuminance, Chromaticity x, and Chromaticity y. Use of this tool will help ensure that calculations for color uniformity are performed consistently.

LED "Life" Issues - Standards Needs - Options

To provide an initial understanding of SSL product life, Mia Paget presented findings from CALiPER long-term testing on SSL luminaires and replacement lamps.[9] While only a limited number of products have been tested under long-term operation by the CALiPER program, the results are nevertheless compelling. A wide range of behavior was observed: products which failed catastrophically, products which depreciated sharply in output during the first few hundred hours of operation, products which displayed some light output depreciation but still produced greater than 70% of initial light output after 6000 or 7500 hours of operation, and products which showed little to no depreciation in light output during this time. A similar wide range in color stability was also observed. No standardized testing method is currently available for performing long-term SSL product testing, so the methods used were also documented and assessed.

Eric Richman led a discussion of the overarching issues surrounding LED "Life." Lumen maintenance and lamp life are critical for SSL products, and are currently partially addressed by LM-80 and TM-21 defining procedures for long-term lumen maintenance testing of LED packages, arrays and modules, and extrapolation of results. SSL product life and reliability does not depend solely on lumen depreciation of the LED subcomponents, so forms of accelerated testing may be needed along with methods for incorporating failure of other components and interactions between system components in SSL product "life" metrics.

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[8] See U.S. Department of Energy, 2007. *ENERGY STAR® Program Requirements for Solid State Lighting Luminaires, Eligibility Criteria – Version 1.0*, http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/SSL_FinalCriteria.pdf, and *U.S. Department of Energy ENERGY STAR® Manufacturer's Guide for Qualifying Solid-State Lighting Luminaires*, September 2008, http://www.energystar.gov/ia/partners/manuf_res/downloads/ENERGYSTAR_Manufacturers_Guide_30Sept08.pdf

[9] CALiPER exploratory report available upon request from the DOE: *Long-Term Testing of Solid-State Lighting, CALiPER Program*, PNNL, January 2009.

Breakout Sessions: Examining SSL Testing

Key objectives of CALiPER Roundtable meetings are to actively engage experts to help guide the CALiPER program, to provide input to standards groups, and to suggest additional testing standards needs. The first day of the roundtable meeting explored a wide array of current topics surrounding SSL testing, with the entire group brainstorming and discussing issues. The experts divided into smaller breakout groups on day 2, to delve deeper into key topics with a goal of prioritizing issues, considering possible solutions and paths forward for the industry toward addressing those issues.

The following bulleted lists summarize the topics addressed in the six breakout groups, along with solutions that were suggested or discussed. The various areas of concern are in some cases overlapping, but for clarity, they are divided into six bulleted lists in the following pages, drawn from the results of the six breakout groups:

A. Subcomponent LED photometry
B. SSL luminaire photometry
C. Meeting market needs for SSL testing
D. ENERGY STAR for SSL general photometry
E. ENERGY STAR lumen maintenance and TMP
F. What industry needs for SSL life testing

A. Subcomponent LED photometry

Context: Subcomponents defined as package, module, array, light engine (and “integrated lamp”)

- Subcomponent photometry may be needed by anyone purchasing, selling, or specifying LEDs
    - OEM
    - Manufacturers: package, array/module, light engine/integrated lamp
    - Thermal/optical design components.

- Issues surrounding subcomponent testing (conditions for tests and methods for tests)
    - More than one form of testing is needed
        - Depends on what type of subcomponent is being tested
        - Depends on who is performing testing for what purpose
    - Junction temperatures may exceed 100°C, limits are increasing over time
    - Testing may be needed at multiple temperatures, but how are temperatures defined
    - Methods may be needed for AC or DC testing and for reference and/or commercial drivers
    - Guidelines for interpolation are needed (between temperature, current, or other curve sets)
    - Guidelines for statistical requirements are needed (how many artifacts, how to handle outliers, standard deviations, etc.)
    - Need to measure color shift under various test conditions as well as output and efficacy
    - Need consistent test methods for comparability and application to systems.

Path Forward: to set testing conditions for reproducible data - develop standardized techniques

- <u>For package</u> – two methods: *Note that both methods must be defined such that they both can produce required sets of temperature/drive curves to relate lumen and color degradation over time and at specified conditions*
    - Active, temperature controlled heat sink method (Y. Zong – NIST)
    - Pulse testing (limited to spot measurement for manufacturer quality control or small automated sphere setup – can’t use goniophotometer, for example). Pulse measurements do not have a defined procedure that specifies test conditions, such as ambient for the test when removed from conditioning chamber/conditions and calibration.

- <u>For module/array</u> – same principles and methods for packages apply here but with *limitations of power, thermal management, and configuration/size that may preference or eliminate one method over another*. Additional recommendations would be needed depending on thermal management and size/configuration of artifacts.
    - For power limitations, use heat sink temperature as the test reference condition.
    - For a heat sink limitations, use pulse method.

- <u>For light engine/integrated lamp</u> – conduct testing in same manner as luminaires (~LM-79)
    - One at 25° C ambient
    - One or more at different elevated ambient temperatures with measured temperature at specified points (TMP), and guidance for taking TMP measurements
    - Potentially modify LM-79 to add this. Modify with guidance on methods for additional generation of curves at different temperatures.

B. SSL luminaire photometry

- Initial test sample thermal stabilization
  - Stabilization interval for a test sample of three measurements 15 minutes apart may not accurately show a stable product (not an issue for labs that stabilize overnight)
  - Potential LM-79 revision
    - Stability intensity data should be plotted
    - Light output should not be trending monotonically.
- Sampling guidelines (selection and quantities of artifacts)
  - Need recommendations to industry regarding how many samples to test and thresholds (for standard deviations, variations, etc.)
  - Recommend production line Q.C. testing for light output and color
  - Investigate correlations between full testing and quick (spot) testing.
- Test conditions vs. reality (laboratory vs. in situ performance)
  - Need investigation regarding application factors for LED luminaires
  - Need temperature reference points in each luminaire
  - Related IES document, "Field Factors for HID luminaire performance"
  - One approach in ENERGY STAR for SSL, in situ TMP testing
  - Recommend further study and possible inclusion of TMP measurement in LM-79.
- Integrating sphere testing (omni-directional vs. directional artifacts)
  - Need more definitive guidance for how well a reference standard must match the beam spread characteristic of the sample
  - Potential LM-79 revision: to address beam spread characteristics of reference standard lamps for testing of directional luminaires or light sources.
- Power factor measurements (specifying impedance and reporting in LM-79)
  - Guidance needed for choosing voltage regulators for reproducible PF measurements
  - Consider guidance in NEMA 410, IEC61000-3-2 Output impedance test requirements (fixed low impedance/wide bandwidth), IEC61000-3-3 Electromagnetic compatibility.
- Measuring color quantities
  - Duv – should be reported (in LM-79 sphere testing results)
  - Are there differences between photometry of white versus color sources?
  - Photo-detectors must be appropriate to the color when testing non-white LEDs, calibrated to each wavelength and color correction factor applied to the data.
- Luminance issues (glare/brightness)
  - Glare assessments are based on point sources
  - Hard to define and measure max luminance for arrays/multi-pin points
  - Recommend human factors study of glare with array sources
  - Need techniques to measure glare (maybe sum the total of each lens around each LED).
- Gonio-spectroradiometry
  - Not yet widespread or well understood, may be a slow process
  - Study needed to compare and correlate gonio-spectroradiometry/integrating sphere.
- Other
  - Humidity
  - Maintenance – dirt depreciation (look to automotive industry testing)
  - Demand for total spectral radiance flux standard for different power
  - Correction factors for photo-detectors
  - Specific guidance needed for luminaires with integral feedback loops.

C. Meeting market needs for SSL testing

- Defining required testing and estimated testing volume
    - Goniophotometry
    - Sphere testing
    - Life testing
    - Other forms of testing
        - Allow options for new testing technologies (lower the barrier to entry for smaller labs)
        - Standards organizations need to keep an open portal for new technology benefit; allows more labs to come on line and lower cost, e.g. LM-77 digital photometry; good, lower cost testing for directional light that can be focused on a screen
        - Temperature testing.

- Quantity of qualified labs: Are there enough labs/personnel?
    - Largely unknown: Past two years have seen significant increases in SSL testing out of overall testing volume
    - Labs hire smart people with relevant degrees and train them which takes about a year
    - Some labs prefer to hire former military personnel accustomed to precise routines and record keeping.

- Lab certification and required documentation
    - Primary barrier for smaller labs is engineer time needed to get initial 17025 compliance
    - Subsequent yearly cost for NVLAP certification may be a consideration
    - NVLAP certification is “painful” but may be necessary.

- Component testing (non-LED, drivers, dimming technology, etc.)
    - Some standards already underway
    - Acknowledge the need for component testing
    - Emphasize requirement to manufacturers.

- Market training – distributors/reps, contractors, end users
    - Recommend basic training to distributors (IES)
    - New DOE fact sheets to help in interpreting SSL testing results.

- Globalization
    - Some countries require in situ testing at specific elevated temperatures depending on applications to weed out inferior product (Korea and Taiwan have standards that control ambient temperature and test at high temps, an attempt to simulate in situ)
    - How to ensure comparability of performance testing results from labs in different countries?

- Reliability/consistency
    - Becoming important concerns.

D. ENERGY STAR SSL issues (general photometry) – current and future

- Lumen and lumen maintenance
    - Current: Should ENERGY STAR for SSL be luminaire-based only?
        - Module, light engine level?
        - Current state of technology – luminaire level only
    - Future: Module efficacy* fixture efficiency = luminaire efficacy?
        - Will require interconnect standards (thermal, electrical, mechanical), light engine measurement standards, module level measurement standards, etc.

- Color
    - Should module level colorimetry be allowed?
        - Luminaire affects SPD and color
        - Similar to CFL-i?
    - Color is mentioned as an issue that hurt the acceptance of CFLs into the marketplace – we do not want to repeat this
    - What about angular color shifts? Currently called "spatial uniformity of color requirement," based on self-reporting
        - Spectro-gonio measurements; other camera based systems.

- General testing requirements
    - CALiPER lab vs. NVLAP accreditation – future will require NVLAP accreditation
    - Tolerance: 10% of measured lumens?
        - Gonio vs. sphere
        - NVLAP proficiency testing will increase information about variation.

- Modularity
    - Future: SSL luminaires will be modular
        - NEMA SSL section is working on an electrical, mechanical, and thermal interface
    - ENERGY STAR replaceable components
        - ES initially approved fixture
        - Can use ES approved replaceable components
            - Extend life of fixture, upgrade, customer choice, reparability.

- Other requirements to consider
    - Requirements aimed at measuring and limiting glare
    - Requirements for equivalency statements on packaging
        - Develop definitions or standards for statements of equivalency
        - Go completely away from a statement of equivalency
    - Efficacy requirements alone may drive poor luminaire design (glare bomb).

E. ENERGY STAR lumen maintenance and TMP

- Laboratory qualification for conducting in situ thermal tests for ENERGY STAR
  - DOE should allow CALiPER labs to conduct in situ thermal tests so that all ENERGY STAR testing can be done in one lab
  - Requirements for labs to qualify to perform the in situ TMP tests must be updated

- Methods for projecting lumen depreciation curves
  - Should ENERGY STAR use TM-21? If yes, then how do we transition to TM-21?
    - Currently TM-21 is under development, so too early to use it
    - Currently TM-21 does not cover color
  - Measurement uncertainty can cause large changes in projected data, which should be studied and addressed.

- LM-80 data and L70 projections
  - Consider use of L70-XX where XX is number of hours of testing used for projection
  - DOE should establish a standard form for LM-80 data submissions.

- Reliability testing – luminaire level
  - Problem – design cycles are as low as 3 to 6 months (components and LEDs)
  - HALT testing requires in-depth study of failure mechanisms to ensure that a non-realistic failure mechanism is not introduced
  - There are no ENERGY STAR provisions for reliability tests at the system level
    - Consider publishing something like, "This is what to consider for a good SSL luminaire design"
    - Consider a NEMA white paper or working with the SSL premium program.

- Reliability testing – integral products and/or light engines
  - No standardized testing procedures available – need to define a testing methodology
  - Can individual component failure rates be combined for an estimated system failure rate?
  - What about activation energies for materials for prediction of failure rates?
  - Should background testing and reporting (by research organizations) be funded to provide recommendations?
    - Define application space – market – to help define reliability test conditions
    - Define test methods
    - What about reliability (REL) models for components to simulate the system?
    - Still need final testing and HALT testing.

- Family testing: Rather than requiring testing at all CCT LEDs, can LEDs be grouped such that LM-80 family testing is performed (same die, same packaging material, possibly only a change in phosphor)?
  - Depends on phosphor system or how phosphor is applied
  - Need better definition of substantial change when related to phosphor – consider testing "least stable" version
  - Consider characterization of phosphors
    - Reliability (REL) models for components to simulate the system
    - Still need final testing and HALT testing.

F. What industry needs for SSL life testing

- What is life?
  - Solid state (lamp) part
  - Electronics (driver) part
  - To consumers, life is:
    - Catastrophic failure (could be the LED module, driver, connections, fixture housing and materials, mounting, etc.)
    - Major color shift
    - Lumen degradation
    - Fixture housing quality
    - Color consistency.

- Considerations for measuring and defining life metrics
  - As per LM-80 for array or module, measure “life” at the chip level for lumen output and color shift at multiple temperatures, then correlate to luminaire “life” based on TMP in the luminaire
  - Factors such as interconnect reliability may need to be tested at complete system level
  - Some products include internal feedback, or internal temperature cut-off, impacting life
  - Should life be based on weak links? With root cause identified for each?
  - In situ testing for outdoor products may differ depending on climates
  - Humidity may impact degradation
  - Application/material notes are not necessarily followed in luminaire design
  - HALT type testing can possibly induce premature failures and affect photometric testing
  - What are uncertainties and confidence levels in life testing options?
  - Can isolated testing be performed for the various failure modes?
  - Should LM-80 or chip/package level testing include pulse width modulation variable, such as frequency and duty cycle (dimming and lumen maintenance capability).

Path Forward:

- Look at all components to identify individual possible *failure type(s)*
  - Driver – *catastrophic*
  - LED “chip” – *catastrophic, lumen output, color shift, uniformity*
  - Array architecture/board materials – *catastrophic, lumen output, color shift, uniformity*
  - Thermal management – heat sink design – *catastrophic, lumen output, color shift, uniformity*
  - Optical components – encapsulate to luminaire/system level – *lumen output, color shift, uniformity*
  - Connections – *catastrophic*.

- Consider as a life measurement path/alternatives
  - Lumen and color change depreciation tests at various temperatures for *chip* or *array* (depending on which goes in luminaire and completed by appropriate manufacturer)
  - Then must also test complete system (luminaire) for *reliability* of added components such as drivers, housing, and lenses
  - Consider guidelines (TM-22?) to define tests needed for components for manufacturers
  - Address catastrophic failures, possibly add this to TM-21.

Next Steps for Key Stakeholder Groups

To facilitate fulfilling the underlying objectives of the roundtable meeting, the implications of each topic area were assembled from the point of view of next steps for each key stakeholder group: industry trade organizations (such as NEMA, NGLIA, etc.), testing laboratories, standards efforts, manufacturers, and the DOE. Many ideas were considered and discussed during the roundtable meeting. The list below assembles the most significant actionable items suggested for each key stakeholder group.

Industry Trade Organizations

Key role—provide guidance for SSL manufacturers

- White papers to consider
  - Provide guidance to manufacturers on how to determine SSL product life, considering all key product components and interactions
  - Establish best practice guidance for determining product ratings (how to characterize a population, quick tests and production line monitoring, product population variation, etc.)
  - Provide guidance oriented to luminaire manufacturers regarding what constitutes good luminaire design for energy efficiency, reliability and application effectiveness (refer to LED chip manufacturer application notes, the upcoming IES LED Design Guide, product labeling practices, etc.)
  - Establish guidance on reliability testing at the system/luminaire level
  - Interconnect standards recommendations (NEMA whitepaper already in process)
- Take roundtable discussion points into consideration for the NEMA SSL premium program concept.

Testing Laboratories

Key roles—implement standardized testing procedures, contribute to refining and developing testing standards

- Join and participate in IES subcommittees developing lighting measurement methods
- Work toward obtaining NVLAP LM-79 accreditation
- Become qualified for ENERGY STAR in situ TMP testing
- Acquire and develop directional standard reference lamps
- Tighten stabilization techniques
- Help with experimentation and data.

Standards Committees

Key roles—develop standard testing methods and technical guidance

- Proceed with TM-21 and consider addressing catastrophic failures
- Refine and extend LM-79 considering the various roundtable recommendations (e.g., reporting guidelines, adding light engine testing guidelines, providing further guidance on stabilization, reference standards, TMP measurements)
- Move forward with LM-XX for heat sink temperature controlled and pulse-testing methods for LED packages and modules
- Move forward with LM-XX or other guidance for generating curve sets enabling characterization of key performance parameters across an array of operating conditions (temperature, current, etc.) for correlation toward in situ performance
- Consider report on in situ application factors for LED luminaires (possibly similar to "Field Factors for HID Luminaire Performance").

Manufacturers (LED, Luminaires, Other)

Key roles—implement best practices, assist standards efforts and DOE

- Join and participate in IES subcommittees developing lighting measurement methods
- Work to further characterize families of LEDs and phosphors
    - Work between LED and luminaire manufacturers on families of products
    - Consider defining and characterizing families of products
- Require explicit reliability information from sub-component suppliers; consider both long term performance shifts and catastrophic reliability as a function of driver current, pad temperature, and other variable factors
- Assist with correlation testing between packages/modules and in situ performance
- Better characterize product performance regarding overall reliability, angular distribution of color, and glare
- Consider sharing statistical product performance information with DOE.

DOE and National Laboratories

Key roles—provide unifying leadership, perform studies, educate, and communicate

- Establish a common format for LM-80 reporting
- Establish mechanism for qualifying independent testing laboratories for in situ TMP testing
- Provide general support to facilitate NVLAP accreditation
    - A preliminary checklist for laboratories seeking NVLAP accreditation
    - Pre-NVLAP quality manual training (ISO 17025 training)
- Perform or motivate testing to study correlations between package/module performance and in situ performance; contribute to refining and validating new LM-XX's being developed for this purpose
- Propose curve set and reporting format for multi-condition characterizations of performance
- Conduct exploratory testing on angular uniformity of color (also called spatial uniformity of color)
- Characterize product population spreads at luminaire and module levels; based on this, revisit recommendations for numbers of artifacts to be tested for various requirements
- Motivate further HALT or other reliability testing, further validate critical components, explore specific forms of reliability testing appropriate for specific applications
- Define minimal sets of interchanged information between suppliers
- Motivate and facilitate manufacturer progress
- Perform study of feasibility of testing on large modules (investigating instrumentation power limits, heat-sinking limits, physical configurations)
- Determine uncertainty estimates for various forms of testing (at both subcomponent and luminaire level); provide guidance for calculations of uncertainty budgets.

Conclusions

Discussions at the 2009 CALiPER Roundtable encompassed a broad array of SSL testing concerns. Different industry actors, different products, and different needs require different forms of testing and present different challenges. Quick testing for quality control purposes in a production line does not entail the same requirements and methods as testing conducted to determine product ratings or to demonstrate compliance with various criteria or codes. Testing of an LED module with no integrated heat sink or driver requires different methodology than testing of a complete luminaire. Basic photometric testing, testing under different operating conditions, and long-term reliability testing presents different challenges. The experts participating in the CALiPER Roundtable grappled with these complex, overlapping questions to determine paths forward for SSL testing and standards.

Industry understanding of SSL testing and standards has progressed rapidly over the past few years as SSL technology and markets mature. The industry can now rely on a number of published standards for SSL performance and look forward to several more which are currently being addressed by standards efforts. Stepping back and visualizing the current status of SSL standards activities, a number of needs are now met (by standards such as LM-79 and ANSI C78.377), so industry experts can now focus efforts on filling gaps.

The CALiPER Roundtable identified specific suggestions for refining or extending current standards efforts and for performing studies or collaborating across various industry groups to explore and validate issues and methods which may not yet be well enough understood or documented for standardization. For subcomponent testing, concrete ideas have been formulated regarding how to set conditions for testing and how to enable correlation between different testing methodologies. For SSL luminaire testing, there is considerable consensus regarding refinements and extensions which can be made to the LM-79 testing standard, to improve consistency of implementation, and to extend coverage to light engines. For both subcomponents and luminaires, in some cases series of tests are needed to characterize performance under a range of operating conditions (such as temperature or drive currents).

Concepts surrounding product life and reliability must be clarified and addressed through concerted studies, ultimately leading to standards or best practices for manufacturers. Industry-wide efforts will be needed to explore options for better characterizing SSL product life, looking at failure modes of all components in an SSL luminaire, increasing our understanding of lumen depreciation and color shift through LM-80 testing and possible depreciation projection methods, and considering forms of accelerated testing which may contribute to more complete approaches toward estimating SSL product life.

It will be valuable for the industry to establish a clearer understanding of uncertainty factors associated with various forms of testing, lending credibility to testing and revealing methods that can be improved or can contribute to determining tolerances for various metrics.

Each stakeholder group has important roles to play to fill the SSL testing and standards gaps. With an enormous expansion in the number of standards efforts underway, there is a clear need for more people to get involved in SSL standards committees—particularly from SSL manufacturers at every level of the industry and from all testing laboratories and trade organizations. DOE will continue to motivate cooperation across the various stakeholder groups, and exploration of new testing concerns.

The concerted effort and constructive, engaged enthusiasm of CALiPER Roundtable participants and other SSL industry leaders is paying off as we see rapid progress and growing credibility of SSL testing. While the list of action items for each stakeholder group is still long, it is increasingly well defined and the industry-wide progress is palpable.

Appendix

List of participants

Name	Company
Berger, Robert	Independent Testing Laboratory (ITL)
Bergman, Rolf	CIE USA (International Commission on Illumination)
Boesenberg, Alex	National Electrical Manufacturers Assoc. (NEMA)
Bradley, Dennis	General Electric (GE)
Brodrick, James	United States Department of Energy (DOE)
Broughton, Kevin	Cooper Lighting – Metalux Research Laboratories
Chesley, Jason	CSA International
Dowling, Kevin	Color Kinetics
Elizondo, Phil	Xicato
Gauna, Kevin	California Lighting Technology Center (CLTC)
Gee, Jason	Lighting Laboratory Inc.
Graeber, Keith	California Lighting Technology Center (CLTC)
Grather, Mike	Luminaire Testing Laboratory
Haraguchi, Kei	Nichia
Hennes, Michael	Illuminating Engineering Society of North America (IES)
Hodapp, Mark	Philips Lumileds
Jackson, Andrew	Philips Lighting Co.
Jenkins, Dave	Orb Optronix
Kurtz, Ronald	International Association of Lighting Designers (IALD)
Lewin, Ian	Lighting Sciences, Inc.
Longo, Steve	OnSpex
Ly, Vireak	Southern California Edison
Marella, Joe	Aurora International Testing Lab
McCullough, Jeff	Pacific Northwest National Laboratory (PNNL)
McKee, Greg	Labsphere
Miller, Cameron	National Institute of Standards and Technology (NIST)
Milz, Erik	Philips Lumileds
O'Boyle, Michael	Lightolier
Ohno, Yoshi	National Institute of Standards and Technology (NIST)
Paget, Mia	Pacific Northwest National Laboratory (PNNL)
Penczek, John	National Institute of Standards and Technology (NIST)
Pistochini, Theresa	California Lighting Technology Center (CLTC)
Richman, Eric	Pacific Northwest National Laboratory (PNNL)
Steward, Heidi	Pacific Northwest National Laboratory (PNNL)
Tirpak, Alan	Optronic Laboratories, Inc.
Tuttle, Ralph	Cree Lighting
Venkataramanan, Venkat	Institute for Optical Sciences, University of Toronto
Wolfman, Howard	Lumispec Consulting
Zong, Yuqin	National Institute of Standards and Technology (NIST)

CALiPER Roundtable 2009

March 3-4, 2009 – Denver, Colorado

Final Agenda

Day 1—Tuesday, March 3, 2009

Format: brief overviews on topics, interactive Q & A, and discussion to capture issues

	Speakers
Welcome & Introductions Quick Update on Standards Activity/Progress Where CALiPER is Today	*J. Brodrick (DOE)* *E. Richman (PNNL)* *M. Paget (PNNL)*
Sub-component LED Photometry Testing Using Controlled Heat Sink Temperature LED Characterization Services Testing LED Light Engines	*Y. Zong & Y. Ohno (NIST)* *D. Jenkins (Orb Optronix)* *Short presentations, Q & A* *Issues Brainstorming*
General SSL Luminaire Photometry Repeatability and Variability in LM-79 Testing Observed Differences in Methods and Reporting Q & A/Brainstorming with Experienced Testing Labs	*M. Paget* *H. Steward (PNNL)* *R. Berger (ITL)* *Short presentations, Q & A* *Issues Brainstorming*
Working Lunch	*Continued discussion*
Update on NVLAP Accreditation	*C. Miller (NIST)* *Short presentations, Q & A*
ENERGY STAR for SSL Photometric Performance Testing *Presentation, Q & A, Issues Brainstorming*	*J. McCullough (PNNL)* *(20 min, 20 min, 20 min)*
General Life Testing CALiPER Long-Term Testing What "Life" Means for LEDs Approaches to Life and Reliability Testing	*Short presentations* *M. Paget* *E. Richman* *Q & A* *Issues Brainstorming*
ENERGY STAR for SSL “Life” Testing *Presentation, Q & A, Issues Brainstorming*	*J. McCullough* *(20 min, 20 min, 20 min)*
Wrap-up on Brainstormed Issues	

Day 2—Wednesday, March 4, 2009

Format: facilitated working sessions, breakouts, identification of paths forward

Breakout Groups (Part 1): Three different topic areas – SSL Luminaire Photometry – ENERGY STAR for SSL General Photometry – What Industry Needs for SSL Life Testing Morning Breakouts Format: – ~35 minutes, review, broaden, refine issues – ~35 minutes, discuss options – ~20 minutes, solutions and path forward	*Facilitated* *Groups of 10-15*
Other Testing Tidbits CALiPER Dimming Study Spatial Uniformity of Color Tool	*Short presentations, Q & A* *M. Paget* *E. Milz & M. Hodapp (Philips Lumileds)*
Breakout Groups (Part 2): Three different topic areas – Subcomponent LED Photometry – ENERGY STAR Lumen Maintenance and TMP – Meeting Market Needs for SSL Testing	*Facilitated* *Groups of 10-15*
Working Lunch	*Continued discussion*
Other Hot Topics (as needed and as possible, CCD, half-moon, benchmarking, TM-21, etc.)	*(Optional, as time permits)*
Afternoon Regrouping: – 15 minute summary per breakout topic – Each team provides brief summary of issues, options, paths forward – Short discussion for each topic area	*Group leads*
Formulate Action Items – Implications for testing labs – Implications for standards efforts – Implications for manufacturers – Implications for DOE CALiPER	*Facilitated discussion*
Wrap-up and Adjournment	*M. Paget*